Testing and Evaluation of Driven Plate Piles in a Full Size Test Slope: A New Method for Stabilizing Shallow Landslides

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ABSTRACT

Shallow rainfall induced landslides in residual and colluvial hillslopes and steep embankments are a common occurrence in many settings. While occasionally posing a threat to property and life-safety, they more often present an ongoing maintenance problem. The Blackhawk Geologic Hazard Abatement District has developed a program to research and develop less costly techniques for arresting unstable slope conditions. A new slope stability mitigation technique was developed consisting of inserting 6-foot long steel piles into and through a potential shallow landslide area. The piles are outfitted with a rectangular steel plate at one end which acts to resist down slope movements of shallow failure masses. As part of a development program sponsored by the District for this mitigation technique, a full-scale landslide test facility was constructed. The test site consists of a 30-foot long by 12-foot wide concrete slope built at a 26.6° inclination upon which landslides and plate pile configurations are tested. The test program has consisted of initiating landslides under extreme saturated conditions on slopes outfitted with and without plate piles. Analyses indicate the technique can increase the factor of safety of shallow depth slopes by between 20% and 50%.

INTRODUCTION

Shallow rainfall-induced landslides in residual and colluvial hillslopes and steep embankments are a common occurrence in many settings [1, 2, 3]. While occasionally posing a threat to property and life-safety, they more often present an ongoing maintenance problem and can lead to the initiation of larger failures. Typically, these slides consist of 2 to 4-foot thick translational movements of silty and clayey soils down slope through the reduction of strength from increases in pore water pressures. Direct surficial infiltration and indirect groundwater seepage are the normative triggers for failure.

In the residential community of Blackhawk, California, located east of the San Francisco Bay, these types of landslides are a common occurrence (Figure 1). However, shallow landslides have also been a repetitive and constant problem along many state highways where steep embankments have been constructed in close proximity to busy thoroughfares. Given the real threat to property values in residential and commercial settings and the constant maintenance problem posed to lifeline structures such as utilities, roadways, and pipelines, new methods to deal with these landslides are needed.

Over the past two years, a new slope stability mitigation technique has been developed and put through a rigorous analytical and field testing program. The technique consists of inserting a grid of 6-foot long, steel angle piles into and through a potential landslide area (Figure 2). The piles are outfitted with a rectangular steel plate at one end which acts to resist the down slope movement of a potential shallow failure mass. Slide forces are transmitted downwards to underlying stiffer materials through the bending strength of the steel. While the technique is similar to the "pin-pile" technique occasionally utilized in large deep-seated landslide repair [see 4, 5, 6, 7 for example], it also conceptualizes a new direction and scope of slope mitigation: the entire shallow slide mass is resisted by the network of plate piles installed with minimal slope disturbance in a cost-effective manner. Initial assessments show that the method can reduce the costs of slope stability mitigation by up to 90% of the cost of traditional "remove and replacement" methods.

In this paper, the plate pile technique is introduced and described in detail. The methodology behind the design and engineering use of plate piles are described. In addition, the results of full-scale field tests performed on a 30-foot long test slope are presented. The results show that the technique is capable of resisting significant down slope forces with an increase in the factor of safety against sliding of up to 50%.

SHALLOW LANDSLIDING AND EXISTING MITIGATION TECHNIQUES

Shallow rainfall-induced landslides often occur in silty clayey soils subjected to dramatic climatic cycles. For example, in the San Francisco Bay area of California, very dry summers lead to cracking and desiccation of the predominantly silty-clayey residual and colluvial top soils, which in turn can lead to an overall strength and compaction degeneration of the soil. When the winter rainy season arrives, these soils tend to soak up large quantities of water, which then lubricate shear planes at the bedrock contact and increase pore water pressures within the soil mass. The increase in water pressures may cause both strength loss in the unsaturated regime from a reduction of effective cohesion, or in the saturated regime from the reduction of effective normal stress on the shear plane. In either case, the cyclic nature of the drying and wetting events is the most common cause of shallow slides in this region. Similar conditions have also been noted in other areas of the United States, specifically the Beaumont clay slopes found along hundreds of miles of freeways in Texas.

FIGURE 1 One of 60 shallow landslides occurring on December 15, 2002 in Blackhawk, California.

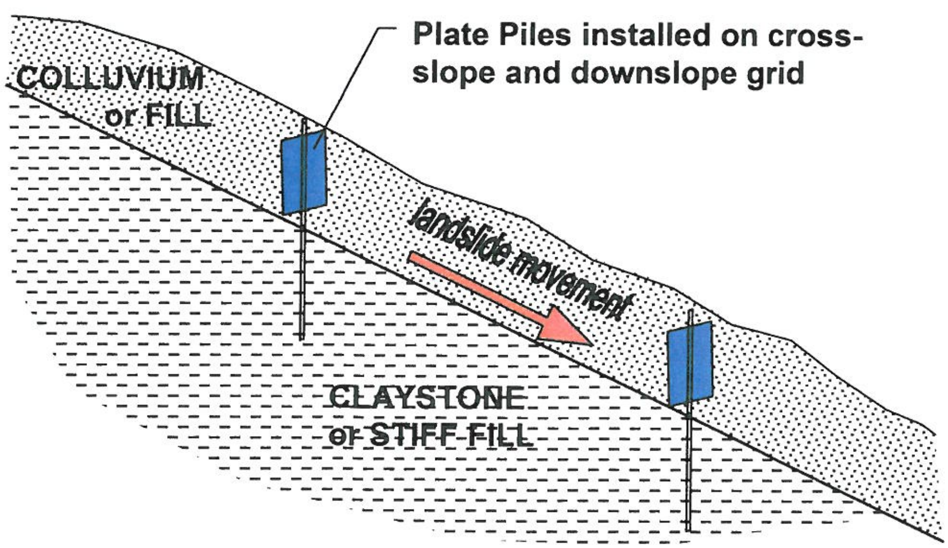


FIGURE 2 Conceptual diagram of Plate Pile Mitigation Technique.

Research on mitigation techniques for shallow landslides has seen some interest from the geotechnical community in the past 20 years, although most recent research has been performed on the predictive analysis of these types of slides [8, 9, 10, 11]. While predictive analysis techniques are an important aspect of understanding slope stability behavior, they do not always assist communities and agencies faced with impending landslides. Once a landslide has begun, it is often too late to try to predict the outcome. Instead, methods of arresting the movement of the slide mass are needed. Existing methods of landslide mitigation have been summarized by Rogers [12]. They include:

- Excavation and recompaction (remove and replacement)
- Conventional retention structures
- Subdrainage
- Soil reinforcement using geomembranes and geosynthetics
- Mechanically stabilized embankments
- Combination mechanically stabilized retention structures

Unfortunately, most of these mitigation options are not applicable to shallow translational slides, mainly due to economic considerations. Retention structures, soil reinforcement options, mechanically stabilized embankments, and combination structures all require large volumes of earthworks in addition to comparatively expensive and time consuming installation methods. For mitigating shallow landslides that are small in area extent, on the order of only several tens of square yards, these techniques require excessive effort and time. For these types of slides, only excavation and subdrainage techniques are immediately applicable. However, these techniques require a substantial on-site and slope renovating presence and may not be applicable where geometric constraints limit the slope grade. Given these limitations and the need to develop a more easily implemented mitigation method, the plate pile technique was developed.

THE PLATE PILE MITIGATION TECHNIQUE

The plate pile mitigation technique (patent pending) is based on increasing a slopes' resistance to sliding through shear stress absorbing bending elements inserted vertically into the slope. In a typical application, the bending elements are 6-foot long, 2 ½ inch angle, galvanized steel sections with a 2-foot by 1-foot, rectangular steel plate welded to one end (Figure 3). The plate piles are driven into a potential slide area typically consisting of 2 to 3 feet of residual or colluvial soil over a stiffer bedrock or fill interface. Being driven piles, the bedrock must be sufficiently weak to allow the insertion of the plate pile without undue stress on the pile tip. To date, plate piles have successfully been installed in claystone and weak sandstone units. The plate acts to reduce the driving forces of the upper slope mass and transfer this load to the stiffer subsurface strata. Plate piles are installed on an offset grid with 4-foot cross slope spacing and 10-foot down slope spacing taking full advantage of the arching effect between adjacent piles.

Thus far, plate piles have been installed in two projects with over 7000 piles in the ground with no problems to date [13]. Individual plate piles are sufficiently light so that they may be maneuvered into position by a single worker. An excavator, outfitted with a 500 lb hoe-ram with a driving head adaptor is then used to drive the plate pile through the weaker surficial soils and into the stronger underlying strata (Figure 4). In situations consisting exclusively of fill, plate piles may be pushed directly into the subsurface layers without the aid of the hoe-ram.

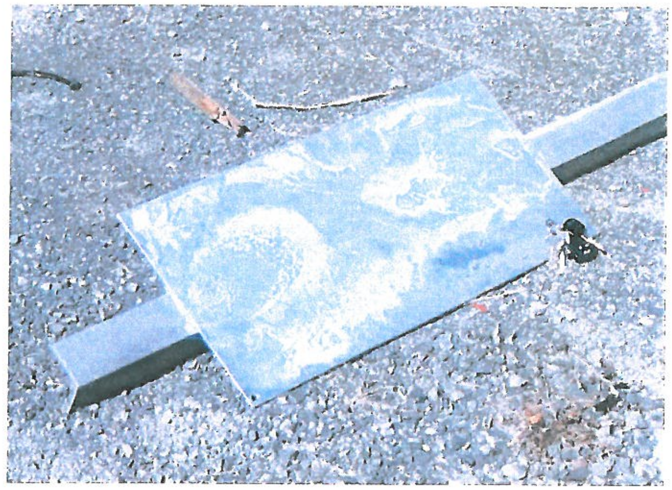
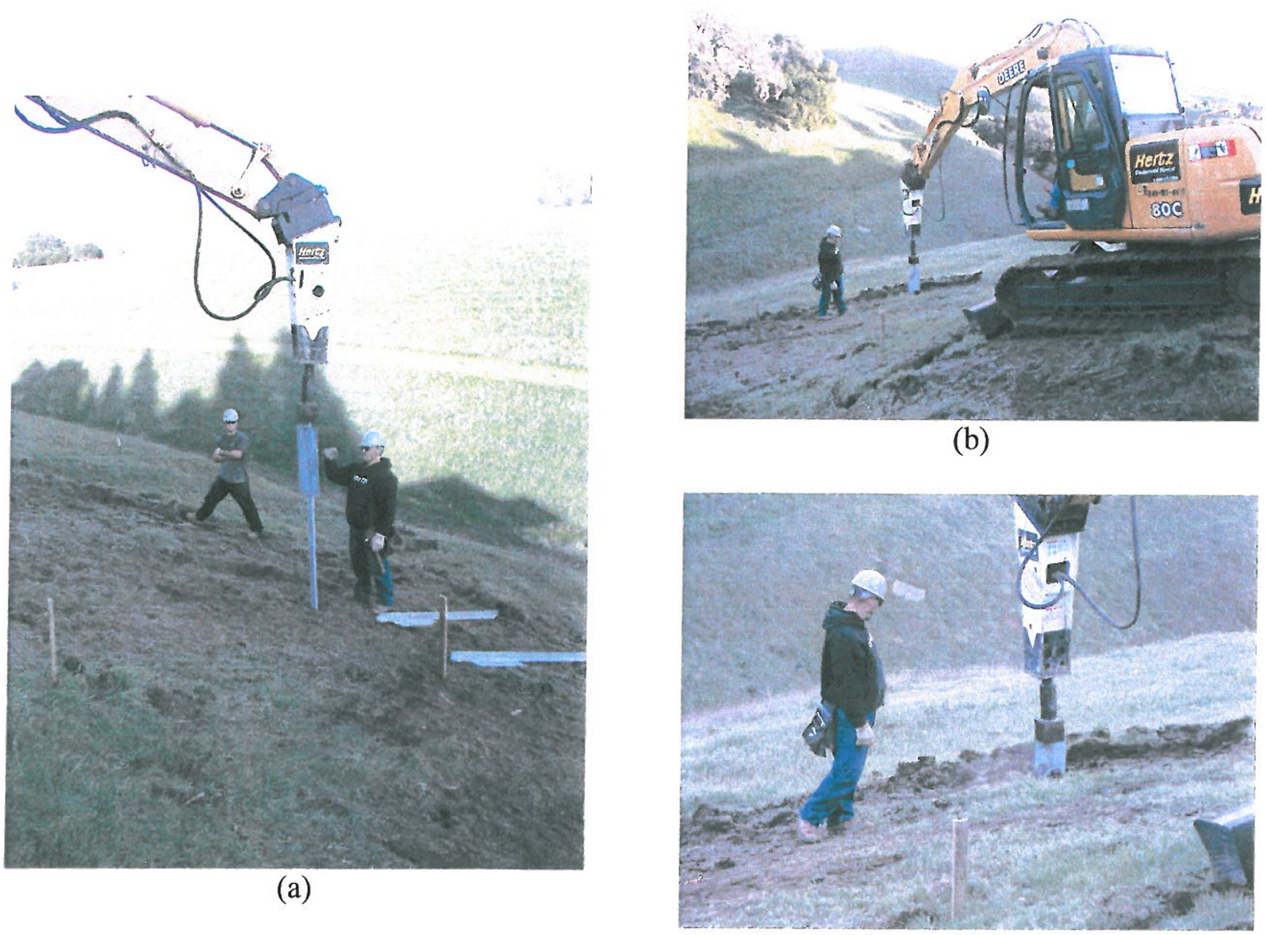


FIGURE 3 Details of typical galvanized steel plate pile.



(a)

(b)

(c)

FIGURE 4 Typical installation of plate piles: (a) alignment of plate pile, (b) driving plate pile into upper colluvium, (c) hoe ram driving into claystone bedrock.

METHODOLOGY: FULL SCALE FIELD TESTING

To test the effectiveness of the plate pile stability method, a series of full-scale field tests were performed at the Blackhawk Geologic Hazard Abatement District (GHAD) Test Site. The test site consists of a 12-foot wide by 30-foot long concrete slope upon which shallow translational landslides can be initiated (Figure 5). Soil is backfilled and compacted on the concrete slab to test specifications and sliding is initiated or attempted through a combined effort of surface irrigation and subsurface infiltration effects. Tests thus far have consisted of a 3-foot thick fill compacted directly on the concrete slab.

The slope is inclined at 26.6° (2H:1V) and outfitted with both surficial and subsurface irrigation systems so that precipitation and groundwater seepage effects can be simulated. The concrete surface mimics a shear plane and a ponding surface so that shallow surficial failures occur on the concrete slope. The 2-foot thick concrete slab is outfitted with a geometric arrangement of PVC tubes in which various configurations of plate piles can be inserted. The concrete slab provides the necessary resistance to the plate piles to transfer shear loads to the deeper subsurface. For control tests in which no plate piles are inserted into the slope and landsliding is initiated, the tubes are capped to prevent infiltration through the slab and to provide a smooth surface for sliding.

FIGURE 5 The Blackhawk GHAD Test Site with bottom irrigation tubes turned on.

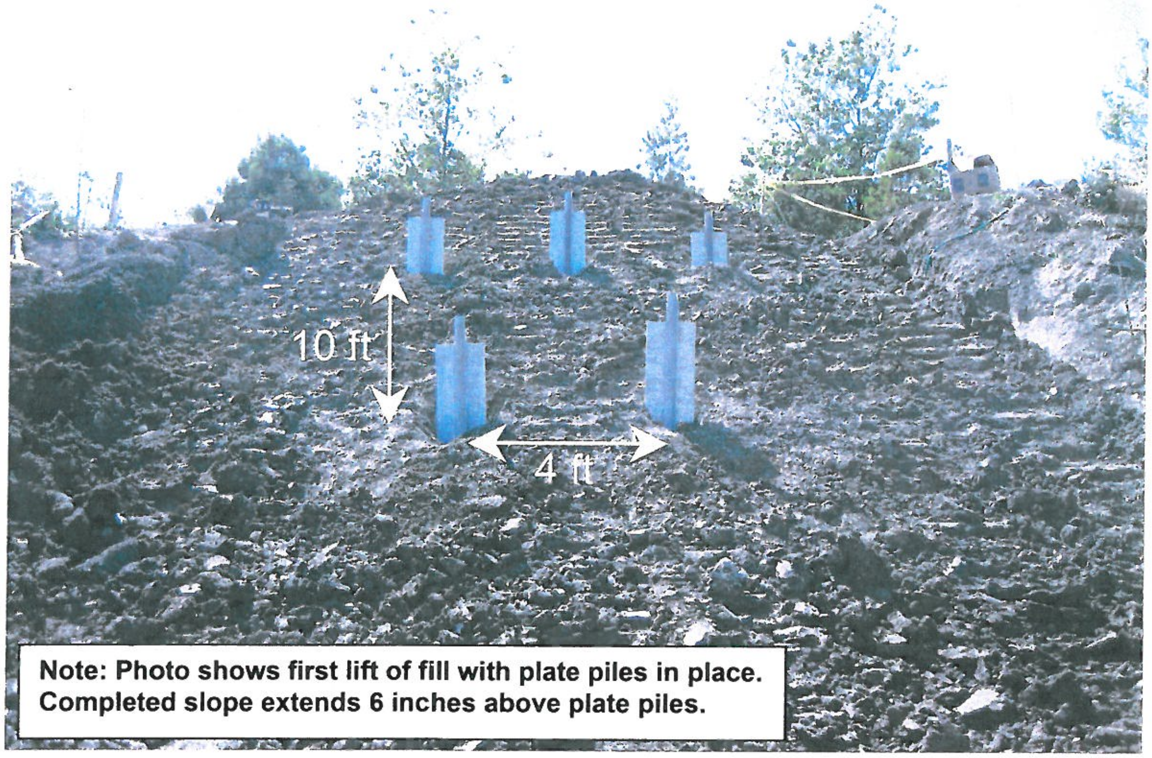


FIGURE 6 Full scale test of 4-ft by 10-ft plate pile grid prior to backfill completion. Six additional plate piles were installed on either side of the concrete pad to complete the array prior to testing.

Test Program

Thus far, two full-scale tests have been performed at the test site. The first test (Test 1) provided control data for future tests with no plate piles installed and the initiation of sliding and mobilization following a strictly monitoring regime of surface and subsurface irrigation. The second test (Test 2) then provided the first full-scale test of the plate pile method: the control slope was recreated and subject to identical conditions, but with two rows of 4-foot cross slope and 10-foot down slope plate piles installed preceding irrigation (Figure 6). Here, failure did not occur.

Test Slope Data

A strict standard of compliance was maintained in each test to verify the homogeneity of the individual test conditions. Soil from a single stockpile was utilized and compacted at nearly identical standards. The soil used in testing represents a typical residual/colluvial soil in the San Francisco Bay area and was obtained from a nearby landslide repair. The soil is a grayish-brown highly plastic silty clay with a peak friction angle of 27° and a peak cohesion of 0.25 ksf. Additional soil properties are summarized in Table 1.

The test fill soil was aerated and allowed to dry in the sun for several weeks prior to testing. This achieved a moisture content value on the dry side of optimum to take advantage of the added strength and higher permeability. The fill was placed and compacted by track rolling in three 12-inch lifts, with a Caterpillar D6-equivalent bulldozer. Two sand cone density tests

TABLE 1 Full Scale Field Testing Soil Properties

Parameter	Value
Soil Classification	
USCS Designation	CH
D_{50} mean grain size	0.004 mm
% < #200 Sieve	77%
Liquid Limit (%)	58%
Plasticity Index (%)	42%
Density and Moisture Properties	
In-situ dry unit weight (typical)	84 pcf
In-situ moisture content (typical)	25%
In-situ moisture content (saturated)	~30%
Optimum dry density (ASTM D698)	104.5 pcf
Optimum moisture content (ASTM D698)	19.0%
Shear Strength Parameters (ASTM D3080)*	
Peak Friction Angle	27°
Peak Cohesion Intercept	0.25 ksf
Residual Friction Angle	26°
Residual Cohesion Intercept	0.10 ksf

* Results are from direct shear samples tested soaked and flooded.

(ASTM D1556) were performed on each test fill to determine the relative compaction of the fill. Test 1 fill was placed at an average of 80.4% relative compaction of the standard effort (ASTM D698) maximum density. Test 2 fill was placed with an average of 80.2% relative compaction, well within the test margin of error. Each test fill was then cut vertically at the toe to remove any buttressing effect and to allow the fill to fail in a mobilized manner.

Test Conditions

Following compaction, surficial irrigation was applied for a period of one hour using two spraying nozzles. The goal of the irrigation program was to obtain field-similar antecedent moisture conditions of the soil prior to full saturation and failure. This wetting phase is therefore consistent with that necessary for typical debris flow initiation as shown by Johnson and Sitar [14]. A total of 625 gallons of water were applied in each case which translated into roughly a 3.5-inch rainfall event as measured by rain gauges installed on the slope. The slopes were then allowed to dry for a 48-hour period under noon-time conditions of 90°F + heat and direct sun. Surficial infiltration was then applied again, this time for a total of 960 gallons and a simulated rainfall event of between 5.5 and 7.5 inches. In Test 2, an additional 50 gallons of water were added to account for higher air temperature and drying conditions on this test date. Subsurface infiltration was then initiated immediately following the end of surficial irrigation through the network of bottom irrigation tubes. In each test, bottom irrigation was turned on for 2 minutes, then turned off for 2 minutes to allow initial wetting of the system. During this time period, 100 gallons of water were injected. The bottom irrigation was then turned on again, this time for a 5 minute period and for a total of approximately 400 gallons injected. Failure occurred at this point in Test 1 and led to a mobilized debris flow mass. No soil mobilization occurred in Test 2 (with plate piles). An additional 5 minutes of subsurface irrigation totaling 220 gallons was applied in Test 2 with still no failure occurring.

RESULTS

Failure of Test 1 occurred as a translative failure, initiating over the entire slope length. Within 3 minutes of prolonged bottom irrigation (5 minutes of total bottom irrigation), tension cracks along the entire slope crest opened as much as 1-inch. Two minutes later, complete failure began, with the entire slope first sliding as a solid mass on the concrete interface, then mobilizing into a thick slurry/debris flow mass. The run-out of the slide mass reached 13 feet beyond the slope toe (Figure 7b). The water content of the side wall of the fill averaged 29.9% with the mobilized debris reaching 38.2%. The test slide morphology represented a typical slide for a residual/colluvial hillslope in the Blackhawk area.

Test 2 did not reach failure and given the nearly identical testing conditions, the role of the plate piles in resisting sliding is self-evident. Here, no tension cracks were observed at the

(a) (b)

FIGURE 7 Test 1 -without plate piles (a) during irrigation and (b) following failure.

(a) (b)

FIGURE 8 Test 2 - with plate piles (a) during irrigation and (b) at end of test without failure.

crest of the slope, nor were any signs of translative movement observed in the supported slope mass. In only one location beneath the bottom row of plate piles did the slope mass move slightly downwards, away from the bottom of the plate piles. This was partially expected since the bottom portion of the slope mass is unsupported. Before and after photos of the Test 1 slope (Figure 7) can be compared with the Test 2 slope photos (Figure 8) for reference.

ANALYSIS AND DISCUSSION

To analytically justify the plate pile methodology, detailed slope stability analyses have been performed using conventional limiting equilibrium techniques to evaluate the effects of the plate piles on the test slope. Both infinite slope and two dimensional method of slices analyses effectively predict the stabilizing effect of the plate piles.

Infinite slope analyses for a 3-foot thick, saturated soil layer with the residual shear strength parameters outlined in Table 1 result in a factor of safety of 1.2. Residual strength parameters are utilized since it is known that these slopes undergo some strength degradation leading to failure. With slightly elevated positive pore water pressures, the factor of safety is reduced to less than 1.0, indicating failure. Thus, failure occurs at some point following saturation after significant wetting.

An infinite slope analysis can also be performed taking into consideration the strength of the plate piles. From previous testing, it is known that plate piles fail in bending at a hinge point located at the midpoint of the steel angle section when subjected to direct loading of the plate. (Figure 9). A yield capacity analysis on the 2½"×2½"×⅜" steel section shows that an equivalent load of 1100 lbs will cause failure of the section when loaded under these conditions. If a nominal amount of bedrock degradation is assumed from the pile driving process, the depth of fixity increases, reducing the equivalent failure load by approximately 10% to 1000 lbs. For a section of slope with this additional resistance, the factor of safety increases by 20%. However,

FIGURE 9 Ultimate strength testing of plate piles with formation of hinge point at yield.

the additional 1000 lbs. of resistance should be viewed as a minimum value since soil backfill resistance behind the plate pile will provide additional strength. Based on full scale field tests, this value is in the range of at least 2000 lbs, which increases the factor of safety by nearly 40%.

Two-dimensional slope stability analyses were performed using the software program SLIDE [15] in a similar manner as for the infinite slope analyses to verify these results. Analyses with plate piles were performed by using the micro-pile support module within SLIDE and show a similar increase in the factor of safety, from a minimum of 30% for the lower end of plate pile resistance to nearly 50% for higher likely values of resistance. The analyses thus explain the lack of failure in the full-scale test slopes – the plate piles are able to resist the driving forces of a saturated soil mass on an inclined slope.

CONCLUSIONS

Plate pile mitigation for shallow landslides provides a new technique for addressing a common landslide hazard. Shallow landslides are most often a maintenance problem, but can also cause serious property damage and be life threatening. The plate pile technique provides a sound, cost-effective method for mitigating these types of slides and can be performed in a multitude of settings. To date, the methodology has been applied for mitigation against shallow residual/colluvial slides in clays overlying claystone and siltstone bedrock and both native and deep clayey fill slopes.

A series of full-scale field tests have been performed to verify the applicability of the technique. In a test performed without plate piles, failure occurred following a carefully monitored irrigation procedure. In a test performed with plate piles, no failure occurred under the same test conditions. These results give credibility to the plate pile methodology.

Slope stability analyses performed for the test slope conditions verify the failure conditions and provide important information regarding the increase in stability of a slope outfitted with plate piles. In general, the results show a 20% increase in the factor of safety against translative sliding failure, sufficient enough to propose this technique in numerous settings.

ACKNOWLEDGMENTS

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